

# Understanding jet quenching and medium response with di-hadron correlation

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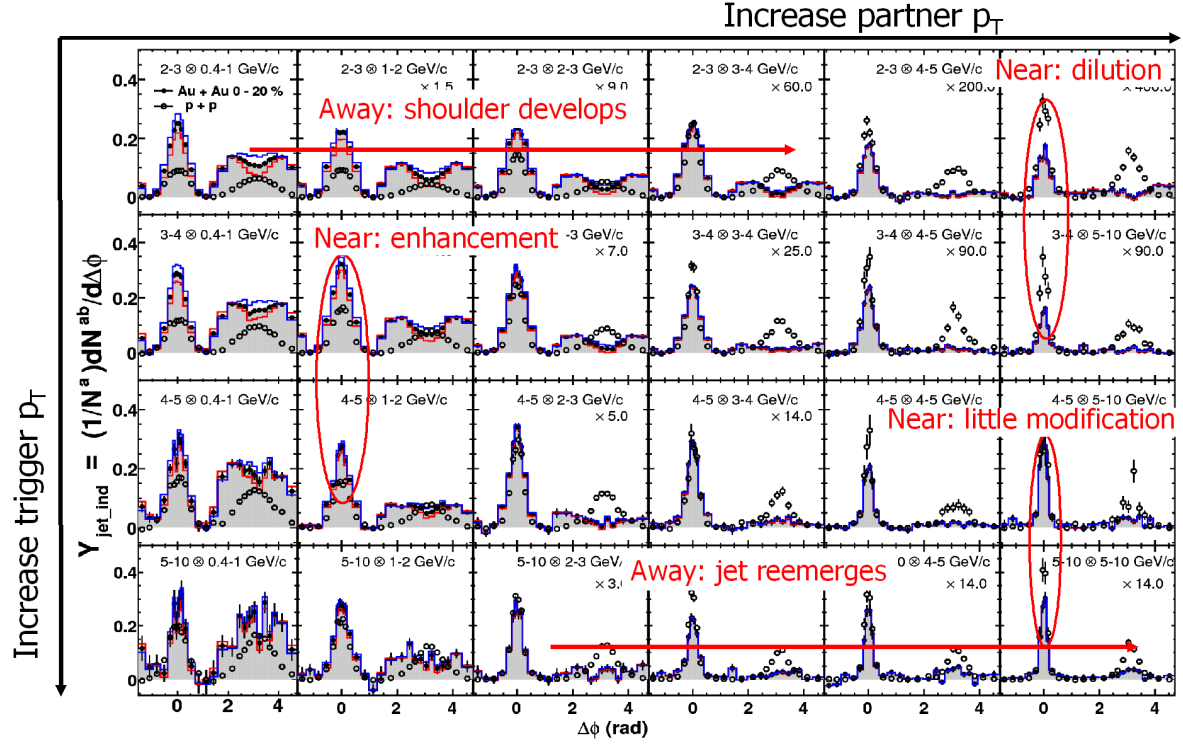
**Abstract.** A brief review of the  $p_T$  dependence of the dihadron correlations from RHIC is presented. We attempt to construct a consistent picture that can describe the data as a whole, focusing on the following important aspects, 1) the relation between jet fragmentation of survived jet and medium response to quenched jets, 2) the possible origin of the medium response and its relation to intermediate  $p_T$  physics for single hadron production, 3) the connection between the near-side ridge and away-side cone, 4) and their relations to low energy results.

## 1. Introduction

Dihadron azimuthal correlation has been a successful tool in understanding the interactions between jet and medium, and in extracting the properties of the sQGP. Over the years, the correlation analyses have been carried out in various regions of transverse momentum ( $p_T$ ) for the triggers and partners. Many interesting features have been discovered. In the high  $p_T$  region, the correlation distributions show narrow peaks around  $\Delta\phi \sim 0$  (near-side) and  $\Delta\phi \sim \pi$  (away-side) [1, 2, 3, 4], consistent with fragmentation of jets escaping the dense medium with small energy loss. In the low  $p_T$  region, the correlation distributions are dominated by a double hump structure around  $\Delta\phi \sim \pi \pm 1.1$  at the away-side (the cone) [1, 6, 5, 3, 4] and a structure elongated along the  $\Delta\eta$  but centered around  $\Delta\phi \sim 0$  (the ridge) [7, 4], characteristic of a complicated response of the medium to energy deposited by the quenched jets.

In the meanwhile, many theoretical models [8] have been proposed to interpret the data. But to date, a complete and consistent picture accommodating the vast amount data is still missing. Our goal is to provide a brief overview of the dihadron correlation results, with an eye towards the reciprocal relation between jet quenching and medium response, and discuss several insights distilled from the data.

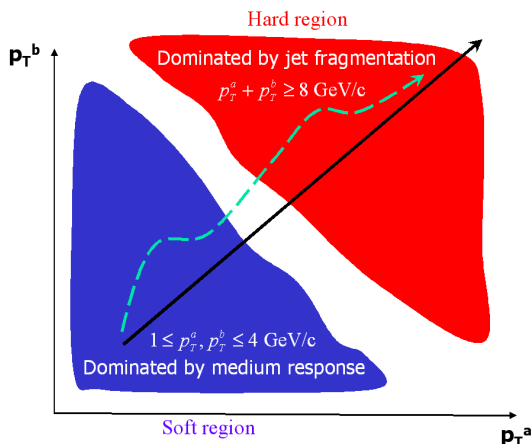
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**Figure 1.** The  $\Delta\phi$  distribution in fine bin of trigger and partner  $p_T$  [4]. Several important features are indicated by the lines and circles.

## 2. Correlation landscape in $p_T^A$ and $p_T^B$

In general the dihadron correlations depend on the  $p_T$  of both hadrons in the pair, and the full characterization of their modification patterns have to be studied differentially as function of trigger  $p_T$  ( $p_T^A$ ) and partner  $p_T$  ( $p_T^B$ ). Such a survey study has been carried out recently by the PHENIX [4] and STAR Collaboration [5]. Fig. 1 summarizes dihadron  $\Delta\phi$  distribution in a broad transverse momentum space, which shows many distinctive features appearing at different  $p_T$  regions (indicated by the circles and lines). These features fits well into a simple two-component picture as illustrated in Fig. 2 separately for both the near- and away-side: a jet fragmentation component that dominates for  $p_T^A + p_T^B \gtrsim 8$  GeV/c, and a medium response component that dominates at  $p_T^A, p_T^B < 4$  GeV/c. The rich  $p_T$  dependent correlation patterns simply reflect the competition between fragmentation of survived jets and medium response to quenched jets on both the near- and away-side. The observed patterns are rather complicated in Fig. 1 since 1) the medium response and jet fragmentation have very different angular distribution and very different spectral slope, 2) the shapes of the medium response are also quite different between the near- and away-side.

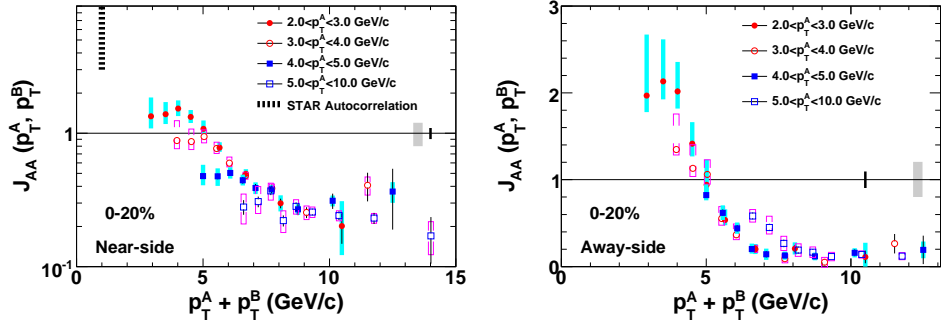


**Figure 2.** A schematic view of the  $p_T$  dependence of the dihadron correlation (applicable for both near- and away-side). The  $p_T^A \otimes p_T^B$  region dominated by jet fragmentation (top right region) and by medium response (bottom left) are indicated. Arrows indicate the possible routes for scanning from low to high  $p_T$ .

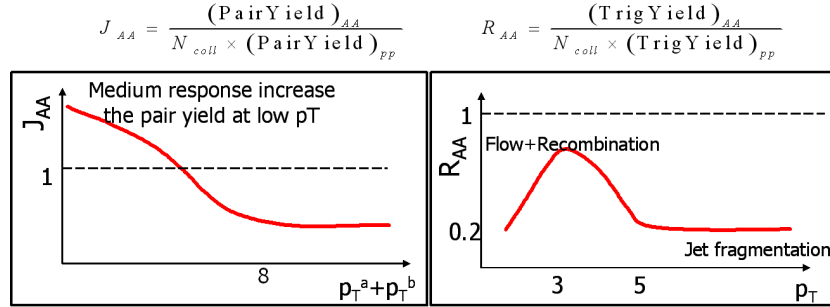
### 3. Medium response

A new variable  $J_{AA}$  was introduced recently to describe the medium response at low  $p_T$  [4].  $J_{AA}$  quantify the medium modification of hadron pair yield from the expected yield, in a way similar to  $R_{AA}$  for describing the modification of single hadron yield. The hadron pair yield is proportional to the dijet yield, and in the absence of nuclear effects, it should scale with  $N_{\text{coll}}$ , and  $J_{AA} = 1$ . Fig. 3 shows  $J_{AA}$  as a function of pair proxy energy ( $p_T^{\text{sum}} = p_T^A + p_T^B$ ) for the near- (left panel) and away-side (right panel). The STAR autocorrelation result [9] is shown as a single point at  $2\langle p_T \rangle \sim 1 \text{ GeV/c}$ . In contrast to a constant suppression at large  $p_T^{\text{sum}}$ , the pair yields are not suppressed or even enhanced at  $p_T^{\text{sum}} < 8 \text{ GeV/c}$ . This enhancement directly reflects the energy transport that redistribute energy of the quenched jets to low  $p_T$  hadrons (medium response). We would like to point out that  $p_T^{\text{sum}}$  is a natural variable for the near-side correlation since it approximates the jet energy, and data show an approximate scaling in  $p_T^{\text{sum}}$ . However, even the data points for the away-side tend to group together, probably because the medium response is a function of jet energy, which increase monotonously with  $p_T^{A,B}$ .

The transition from jet fragmentation dominated to medium dominated region in dihadron correlation happens around  $p_T \sim 4 - 5 \text{ GeV/c}$ , a region similar to that for the single particle from soft physics (hydrodynamics+ recombination) dominated region to hard physics (jet) dominated region. Naturally, we expect the physics important for single particle production should play an important role for the dihadron correlation. Fig. 4 shows schematically the  $p_T$  dependence of the modifications of the single particle yield (via  $R_{AA}$ ) and hadron pair yield (via  $J_{AA}$ ). Their  $p_T$  dependence trend are quite different, especially at low  $p_T$ , which can be explained qualitatively as follows. Even though jet production dominates single particle yield at  $p_T > 2 \text{ GeV/c}$  in  $p + p$  collisions, the strong energy loss and collective flow modify the  $p_T$  distribution by shifting hard hadrons to lower  $p_T$  and pushing soft hadrons to higher  $p_T$ . This reshuffling changes single-hadron and correlated hadron-pair yield, hence the  $R_{AA}$  and  $J_{AA}$  shape. Indeed, several theoretical models suggest that collective flow and recombination play a



**Figure 3.** The modification factor for hadron pair yield as function of  $p_T^{sum} = p_T^A + p_T^B$  for the near-side (left) and away-side (right).  $p_T^{sum}$  condenses the 2-D correlation data in  $p_T^A$  and  $p_T^B$  space into a one dimensional plot. The STAR auto-correlation result [9] is divided by 3 (the lower end) to normalize the  $\eta$  acceptance relative to PHENIX.

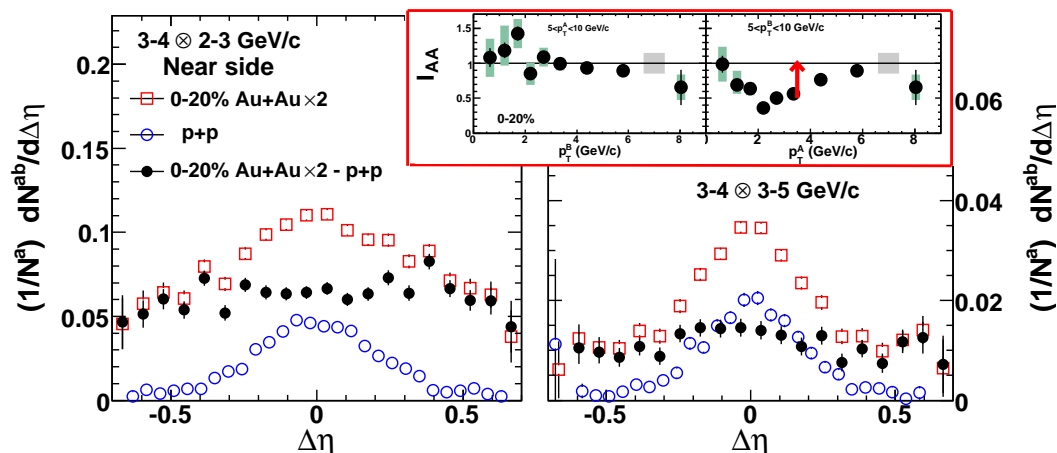


**Figure 4.** Schematic view of the  $p_T$  dependence modification for single hadrons (right panel) and hadron pairs (left panel).

significant role in modifying the angular shape, spectra slope and particle composition of the correlated pairs [8].  $J_{AA}$  provides a mean to quantify the contribution of jet fragmentation hadrons or jet induced hadrons in this  $p_T$  region.

#### 4. Dilution of per-trigger yield by non-fragmentation hadrons

Previously, the modification of dihadron yield is characterized with  $I_{AA}$  (ratio of per-trigger yield between Au+Au and  $p + p$ ) [10].  $I_{AA}$  is a good variable at high  $p_T$ , since most triggers come from jets and most jets fragment into at most one trigger, such that per-trigger yield (PTY) is a good representation of per-jet yield. However at lower  $p_T$  region, non-fragmentation triggers from soft production mechanisms or medium response mechanisms become important. These triggers tend to dilutes the  $I_{AA}$ , since they either has no correlation or non-jet like correlation (such as ridge). Fig. 5 illustrate the dilution effects for near-side  $\Delta\eta$  correlation. We estimate dilution factor ( $\sim 2$ ) for 3-4 GeV/c triggers based on their correlations with 5-10 GeV/c hadrons as shown by the inserted panel: requiring 5-10 GeV/c hadrons ensures the pairs are dominated by the jet fragmentation (left panel of the insert), thus deviation of  $I_{AA}$  from



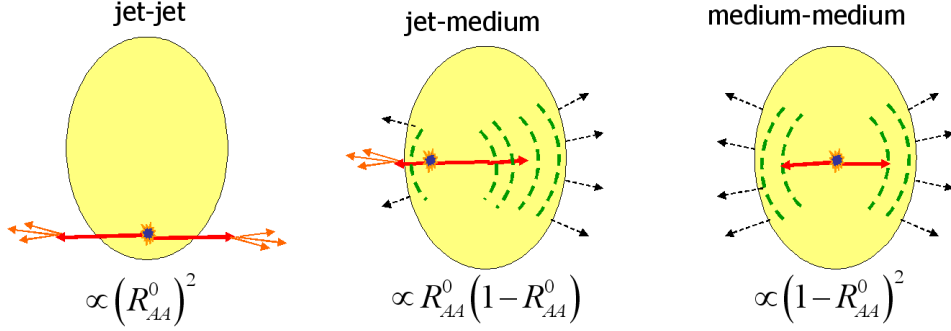
**Figure 5.** Per-trigger yield  $\Delta\eta$  distribution for 3-4 GeV/c triggers and two parton  $p_T$  selections. The ridge distribution (solid circles) is estimated by subtracting the Au+Au distribution corrected by dilution effect (open squares) minus the p+p (open circles). The dilution correction ( $\times 2$ ) is indicated by the red arrow in the inserted panel (see text for explanation).

one for soft triggers reflects the level of dilution (the red arrow). Once the dilution factor is corrected, we subtract out the jet fragmentation contribution and obtain the ridge distribution (black circles). The estimated ridge contribution is approximately flat, consistent experimental data at large  $\Delta\eta$ . However, this dilution effect was not observed in some STAR analysis [11, 12], which shows that the  $PTY_{AA}$  subtracted by the estimated ridge before any dilution correction already equals  $PTY_{pp}$ .

## 5. Origin of correlated pair and connection between near-side ridge and away-side cone

In most correlation analyses and model calculations, it was normally assumed that one hadron (“trigger”) comes from the jet, and the second hadron (“partner”) comes from either fragmentation or feedback, i.e. only jet-jet and jet-medium pairs are considered. In this picture, the trigger comes from a jet that is biased to the surface, which losses some energy and fragments outside the medium. The fragments contribute to the near-side jet peak, and the feedback of the lost energy gives rise to the near-side ridge. In parallel, the away-side jet is quenched as it traverses a longer medium, contributing to the away-side cone.

This picture does not include the medium-medium pairs (both hadrons come from medium feedback of quenched jets). These pairs could be important at intermediate and low  $p_T$ , since each jet can induce more correlated hadrons via jet quenching than via fragmentation. For example, most medium response models induce correlation by local heating of medium by the jet, such as momentum kick, jet deflection, mach-cone, etc [8], which are very effective in generating large yield of correlated hadron pairs. In addition,



**Figure 6.** The geometrical origin of the jet-jet (left), jet-medium (middle) and medium-medium (right) pairs. Their production rate scale with the volume of the emission points, which is proportional to  $(R_{AA}^0)^2$ ,  $R_{AA}^0(1 - R_{AA}^0)$ , and  $(1 - R_{AA}^0)^2$ , respectively ( $R_{AA}^0$  is the constant suppression level at high  $p_T$ .)

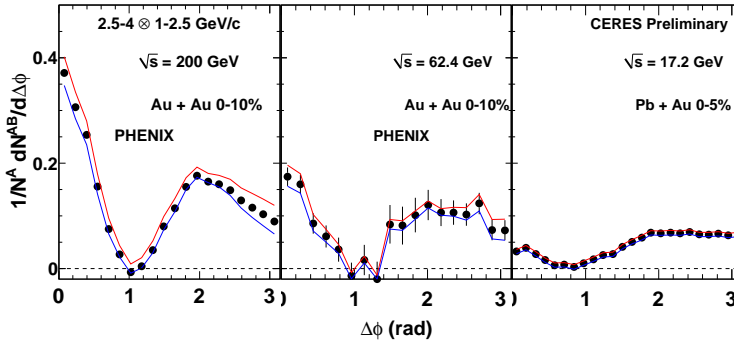
the whole overlap volume contributes to the observed medium-medium pairs, while both jet-jet and jet-medium pairs suffer a strong suppression. This point is illustrated by Fig. 6, which shows the typical geometrical origin for the three types of correlated pairs. The jet fragmentation contribution is proportional to the number of survived jet ( $\propto R_{AA}^0$ , i.e. the constant suppression level at large  $p_T$ ,  $R_{AA}^0 \approx 0.2$  in most central bin.), while the medium response is proportional to the number of quenched jets ( $\propto 1 - R_{AA}^0$ ). For jet-jet pairs, both hadron are emitted from the surface (tangential emission); for jet-medium pairs, the jet hadron is emitted from the surface (surface emission) and the other from the whole volume; for medium-medium pairs, both hadrons are emitted from the whole volume. The production rate for jet-jet, jet-medium and medium-medium pairs scale approximately with  $(R_{AA}^0)^2$ ,  $R_{AA}^0(1 - R_{AA}^0)$  and  $(1 - R_{AA}^0)^2$ . Clearly, if  $R_{AA}^0 \rightarrow 0$ , the medium-medium pairs becomes dominant.

Recently, several analyses have been carried out to quantify the properties of the near-side ridge and away-side cone structures [11, 12, 13, 14, 15, 4]. The data show very similar properties between the ridge and the cone, i.e. both have similar slope and bulk like particle compositions, and both are important up to 4 GeV/ $c$ . These similarities suggests that their production mechanisms are connected. The medium-medium pairs from quenched jets are natural candidates for creating these similarities. Because medium-medium pairs come from quenched jets originated deep inside the medium, they contribute to both the near-side and away-side on a equal footing. The near-side pairs could contain correlations among mach cone particles, and away-side pairs could also contain correlation between the ridge and mach cone particles (see Ref. [16] for a possible realization).

## 6. Energy dependence and three-particle correlation

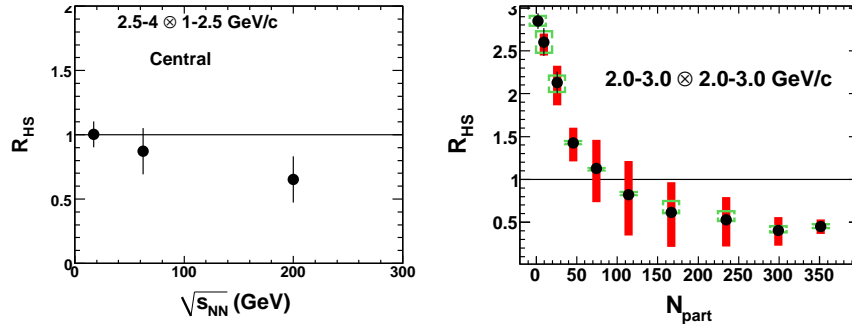
A strong modification of the away-side correlation was also observed at the top SPS energy ( $\sqrt{s_{NN}} = 17.2$  GeV) [17]. The strong away-side broadening has been used to

argue for a similar interpretation (such as mach cone) as for the RHIC results. However a quantitative analysis of the energy dependence of the modification patterns (see Fig.7) shows that the yield of medium response are quite different between RHIC and SPS energies. In fact the near-side yield drop by almost factor of 8 going from 200 GeV to 17 GeV while the away-side shoulder yield drops by factor of 2 in the same energy range. But there are little dependence of the yields on  $\sqrt{s}$  in the away-side head region, where the jet fragmentation is important. To quantify the energy dependence of away-side shape, we calculate the ratio of the yield density in the head region to that in shoulder region,  $R_{HS}$  [3], in Fig.8a. The  $R_{HS}$  increases with decreasing collision energy, with a ratio slightly above one in SPS energy. This value is comparable with that obtained for rather peripheral ( $N_{part} = 70$ ) in Au+Au collisions at 200 GeV (Fig.8b). These results suggest a much weaker medium response in SPS energy (the ridge almost disappeared and cone strongly suppressed) than that at RHIC, but a similar jet fragmentation contribution, probably related to smaller energy loss and stronger Cronin effects at lower energy [18].



**Figure 7.** The  $\Delta\phi$  distribution in central collisions for three collision energies in central collisions.

Lastly, it was shown that the mach-cone angle found from the three particle (3-p) correlation (1.4 rad) is significantly larger than the two particle (2-p) correlation analysis (1.1 rad). SPS also seems to see a 3-p correlation signal [19]. However one should realized that, it is possible that the kinematics of jets contributing to 3-p signal



**Figure 8.** (Left) The  $\sqrt{s}$  dependence of the  $R_{HS}$  calculated from Fig.7. (Right) centrality dependence of  $R_{HS}$  for a lower  $p_T$  bin in  $\sqrt{s_{NN}} = 200$  GeV Au+Au collisions [4].

is different from those contributing to the 2-p signal. It is likely that most jet have multiplicity  $< 3$  that the 3-p only samples a small fraction of all jets that contribute to the dihadron correlations.

## 7. Discussion

Due to the surface bias and steeply falling parton spectra, the observed high  $p_T$  single hadrons and dihadron pairs mainly come from those jets that suffer minimal interaction with the medium. This energy loss bias limits their usefulness as tomography tools. On the other hand, medium responses are directly sensitive to the energy loss and energy dissipation processes used to model the high  $p_T$  production. For example the collisional energy loss would imply that momentum kick dominates the low  $p_T$  pairs, the radiative energy loss would favor for the gluon feedback mechanism. Finally, the jet quenching and medium responses are modeled separately in most theoretical calculations. A unified framework, including both jet quenching and medium response, which can describe the full  $p_T$  evolution of the jet shape and yield at both near- and away-side is required to understand the details of the parton-medium interactions.

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